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FREQUENCY RESPONSE TESTING AT EXPERIMENTAL BREEDER REACTOR II USING DISCRETE-LEVEL, PERIODIC SIGNALS*

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ABSTRACT

The Experimental Breeder Reactor II (EBR-II) reactivity-to-power frequency-response function was measured with pseudo-random, discrete-level, periodic signals. The reactor power deviation was small with insignificant perturbation of normal operation and in-place irradiation experiments. Comparison of results with measured rod oscillator data and with theoretical predictions show good agreement. Moreover, measures of input signal quality (autocorrelation function and energy spectra) confirm the ability to enable this type of frequency response determination at EBR-II. Measurements were made with the pseudo-random binary sequence, quadratic residue binary sequence, pseudo-random ternary sequence, and the multifrequency binary sequence.

INTRODUCTION

Frequency-response testing is a dynamic analysis technique routinely applied to nuclear reactors to access the system stability margin, check mathematical models, and generally provide information enabling system performance improvement. Reactor dynamic experiments are routinely done at EBR-II to analyze the dynamic characteristics of the fast reactor system in which frequent changes are made in the number and type of experimental subassemblies.

Experimental techniques used in the dynamic analysis of EBR-II in the past have used the drop rod and the rotary oscillator rod. Rod-drop experiments drop a normal worth control rod from the core and collect the resultant time-dependent power history (1). The feedback reactivity is obtained by applying an inverse kinetics analysis to that time-dependent power shape. Although test implementation is straightforward, rod drop data are difficult to analyze because the finite signal energy is distributed over a wide range of frequencies; the reactor power perturbation can be large. The rotary rod-oscillator experiment introduces sinusoidal reactivity perturbations by axially rotating two adjacent cylinders. Although this method yields a direct analysis, equipment and operational constraints have limited its usefulness at EBR-II. Despite the disadvantages of this and the rod-drop technique, a number of successful tests have been conducted at EBR-II as illustrated in Ref. 2.

The frequency-response testing technique employing pseudo-random, discrete-level, periodic signals has wide acceptance as an alternative to the methods previously used at EBR-II. Kerlin describes the application of this technique and provides several examples (3). It offers the advantages of reduced experiment time, fewer equipment problems as associated with the rod-oscillator, and improved accuracy over the rod-drop technique. Furthermore, several frequencies can be analyzed in a single test with minimum reactor perturbation. This is particularity important for EBR-II which has an on-going program as a materials irradiation test facility.

This study reports on the application of pseudo-random, discrete-level, periodic signals to measure the frequency response function at EBR-II. The test program used the Automatic Control Rod Drive System (ACRDS), installed in 1984, to move a control rod in a programmed, periodic manner. The Dynamic Simulator for Nuclear Power Plants (DSNP) (4), a continuous systems simulation language, was used for prediction and analysis of the experimental results. The frequency response was calculated as the ratio of the Fourier transform of the system output (power level) to the Fourier transform of the input (reactivity perturbation). Frequency response results are compared with the zero-power frequency response function and rod oscillator data. This report also compares simulated results from DSNP with the experimental data.

EQUIPMENT DESCRIPTION

EBR-II is a pool-type LMR with complete submersion of the reactor core, reflector, blanket, neutron shield, primary pumps and piping, heat exchanger, and in-vessel fuel handling equipment in liquid sodium. Primary pumps take suction from the pool of liquid sodium and send the coolant to high and low pressure plena which direct flow to the core and blanket regions, respectively. The exiting coolant flows to an intermediate heat exchanger via an interconnecting "Z" pipe for subsequent discharge into the sodium.

Installation of the ACRDS, enabling manual or automatic operation of a control rod, is described by Larson in Ref. 5. The ACRDS rod is restricted to a total reactivity worth of 0.90 \$. (This worth is slightly more than the average worth of each high-worth control rod in EBR-II). A least-squares fit to a fourth degree polynomial using measured control rod calibration data describes the position-dependent rod worth.

The ACRDS includes a controller, a direct current rod drive motor, and gear train; it uses the existing EBR-II control rod rack and pinion gear system, scram system, and position synchro transmitters. A digital computer uses rod position, rod velocity, or reactor power signals to provide a demand signal to the rod drive controller. Separate motor controllers operate in manual and automatic mode. Maximum motor speed is limited to less than that of a reactivity insertion rate of 0.12 \$/s. To provide sufficient margin to this limit, the ACRDS has a maximum rod worth rate of 2.76 \$/m (0.07\$/in.) and a maximum rod speed of 0.0309 m/s (1.22 in/s). The velocity signal is examined by the computer to provide additional assurance that the 0.12 \$/s limit is not exceeded during automatic operation.

TEST SIGNALS SELECTION AND IMPLEMENTATION

The term pseudo-random is applied to certain discrete-level, periodic binary and ternary signals that possess autocorrelation and power spectrum characteristics similar to a Gaussian white noise signal, which autocorrelates to a delta function and has a flat power spectrum. These characteristics enable several harmonic frequencies to be analyzed in a single test. The signals are characterized by their period (T), bit size (Δt), and number of bits per period (Z). Test signals applied in this study were the *m*-sequence pseudo-random binary sequence (PRBS), quadratic residue pseudo-random binary sequence (QRBS), pseudo-random ternary sequence (PRTS), and the multifrequency binary sequence (MFBS). With the exception of the MFBS, selection of the above parameters fixes the signal energy spectral shape. Methods of generating these signals are well known (3,7). The MFBS generation technique developed by Buckner (8) puts 70 to 80% of signal energy in the harmonics of interest. The PRTS and MFBS are anti-symmetric (discriminate against non-linear effects) whereas the PRBS and QRBS are not.

Test signal selection demanded a range of interest with adequate signal-to-noise ratio (S/N). Concern about perturbing in-place irradiation experiments and exciting system non-linearities were factors in selecting 0.01 \$ as the signal amplitude common to all signal types. This corresponds to a power swing of about ± 1% which has been found successful (3) at achieving the above objectives. Table I details the characteristics of the selected test signals.

TABLE I
Characteristics of the Pseudo-random, Discrete-level Signals

Type of Sequence	No. of Bits	Bit Size (second)	Period (seconds)	No. of Periods	Reactivity Amplitude ($)
QRBS	47	0.55	25.85	6	0.0056
QRBS	47	0.55	25.85	6	0.0112
QRBS	47	0.55	25.85	6	0.0168
PRBS	31	0.45	13.95	6	0.0112
MFBS	140	0.55	77.00	6	0.0112
MFBS	140	0.55	77.00	6	0.0056
PRTS	26	0.50	13.00	6	0.0056

The lowest frequency of interest established the signal period and the upper frequency of interest (needing one-half the fundamental frequency energy) established the bit size. This leads (3) to the useful frequency range of $1/T \leq$ frequency (Hz) $\leq 0.44 / \Delta t$.

The EBR-II feedback transfer function obtained from previous reactor dynamic testing and analysis (5), was used in the specifications and generations of the MFBS:

$$H(s) = \sum_{i=1}^{I} \frac{A_i}{(1 + s\tau_i)}, \qquad (1)$$

τ_i are system heat transfer time constants and A_i are the associated weighting function or residue in terms of reactivity change in dollars per fractional power change. Values are provided in Table II.

TABLE II
EBR-II Feedback Transfer Function Parameters

i	Time Constant (τ_i) (second)	Frequency Corresponding to System Time Constant, (Hz)
1	4.0	0.03979
2	2.0	0.07958
3	0.4	0.3979
4	0.2	0.7958

The MFBS was chosen to maximize signal energy at these four frequencies. Because of its anti-symmetric character (even harmonics have zero energy) the fundamental MFBS frequency was set at 1/3 of 0.03979 Hz. The shortest time constant and the mechanical features of the ACRDS dictated a bit size of about 0.5 second. These signal requirements lead to a 140 bit sequence with a 0.55 second bit size. Correspondence between the desired frequencies and those obtained with this MFBS is shown in Table III. Further improvement is possible by increasing the number of bits and signal period, but these values quickly become prohibitively high.

TABLE III
Correspondence of 140 bit MFBS Frequencies with EBR-II System Time Constants

Harmonic	MFBS Frequency (Hz)	Frequency Corresponding to System Time Constant (Hz)
3	0.0390	0.0398
7	0.0909	0.0796
31	0.4026	0.3979
61	0.7922	0.7958

The QRBS was designed to exploit its non-zero even harmonics enabling a fundamental frequency of 0.0387 Hz. A 47 bit sequence resulted in the same bit size and frequency span as the MFBS signal, but with a shorter period. In an effort to investigate the effect of signal amplitude, multiple amplitude tests were conducted with the MFBS and QRBS signal. PRBS and PRTS sequences, of shorter periods and similar bit size, rounded out the experimental design.

TEST IMPLEMENTATION

The test program consisted of a reactor shutdown experiment and an at-power experiment. Fifty-eight MWt was selected to allow comparison with previous reactor dynamic tests (2). The rod travel in the experiments ranged from ± 2.03 to ± 6.10 mm (± 0.08 to ± 0.24 in.) resulting in a reactivity perturbation of ± 0.0056 $ to ± 0.00168 $, respectively. The shutdown experiment verified the pseudo-random character of the input signals and proper ACRDS implementation of the signals.

During the at-power experiment test, signals were implemented by the ACRDS computer (with the pre-programmed test signals) in a closed-loop rod positioning control technique (9,10). The power level signal was obtained from a compensated ion chamber and, along with other selected plant parameters (e.g., ACRDS rod position), was recorded and digitized at a 0.05 second sampling rate.

DATA ANALYSIS

DSNP was used to determine the frequency response by applying the fast Fourier transform algorithm. Each test signal contained six periods of which the last five were analyzed individually enabling a 95 % confidence interval determination. In addition, the last four periods of each test signal were analyzed by the FFT to minimize noise error contamination. The signal sampling rate and method of Fourier analysis maintained the Nyquist frequency well above 1.7 H_z. DSNP was modified to generate the sequence patterns, simulate plant response, predict the experimental results, and analyze the data. Data analysis included autocorrelation and power spectra determination of the input signal.

RESULTS

Input signal quality was evaluated by autocorrelation function and power spectra. The autocorrelation data of the binary sequences possessed the delta function characteristics of a spike at intervals of one period and a negative bias of 1/2 between spikes. Further, the side lobes characteristic of finite period signals were also observed. Fig. 1 shows the auto-correlation function obtained from the first three periods of 47 bit QRBS test. The autocorrelation results of the PRTS test were also as expected (a series of spikes with alternating sign separated by 1/2 period and side loops of width Δt and no bias). However, blips were observed on either side of the side loops indicative of signal imperfection.

Power spectra were determined and compared with ideal signal characteristics. The PRTS and high amplitude QRBS where the only signals that did not retain at least 50% of the fundamental frequency power in the $0.44/\Delta t$ harmonic. This is attributed to signal imperfection. Further, the intermediate or "zero" state position of the PRTS was found to be slightly dependent on the originating position. The problem of determining the rod position accurately for a three-level signal was previously observed at the MSRE (6). One of the advantages of the MFBS is shown by the power spectra of the 140 bit MFBS in Fig. 2 where four target frequencies received 63.9% of total signal power.

The frequency response results for the anti-symmetric sequences (last 4 periods analyzed as one) are shown in Fig. 3. Agreement of the results obtained with the MFBS and the rod oscillator data is excellent. The corresponding nonanti-symmetric signal frequency response results are shown in Fig. 4. Agreement is good in the range of 0.1 to 1 Hz but data points fit less weld below 0.1 H_z. Nonlinear feedback effects (e.g., subassembly bowing) (2) may influence this frequency range. The superior performance of the MFBS over the nonanti-symmetric signals is attributed to the higher signal power and its discrimination against nonlinear effects.

Figures 5 and 6 compare MFBS and PRTS results obtained from the individually analyzed periods with DSNP predictions, including experimental determination of the 95% confidence interval for the mean. The superiority of the MFBS to the PRTS is attributed to the higher harmonic signal energy and difficulties associated with three states. DSNP predictions compare well with experimental results: DSNP predicts less feedback in the higher end of the frequency range analyzed indicative of the standard EBR-II policy to use conservative parameters. Finally, the coefficient of variation (COV) of the results obtained with the MFBS and QRBS signals is shown in Figure 7. Advantages of the MFBS are clearly those which result from signal strength in selected frequencies, but at the expense of fewer experimental frequencies.

CONCLUSIONS

Pseudo-random, discrete-level, periodic signals were successfully implemented to measure the reactivity-to-power frequency response function at EBR-II. Comparison of results between MFBS frequency response data and previous rod oscillator experiments show good quantitative agreement. Further, the one cent reactivity perturbation MFBS concentrated 64% of the signal power into the four frequencies associated with predominant feedback time constants.

Comparisons were made of the different test signals. As expected, the MFBS test resulted in greater accuracy due to a higher signal-to-noise ratio. This and its antisymmetric characteristic proved essential in the low frequency range generally associated with nonlinear feedback effects (e.g., subassembly bowing). The PRTS did not result in improved accuracy over a PRBS of similar signal strength. This is attributed to practical problems of implementing a three level signal. Thus, although it discriminates against nonlinear effects the PRTS is of limited usefulness at EBR-II. QRBS and PRBS signals possessing one cent reactivity perturbations retained at least half as much power as the largest harmonic out to the theoretical harmonic limit (0.44 Z). Therefore, the ACRDS was demonstrated to sufficiently emulate multiple types of discrete-level pseudo-random signals tailored to EBR-II.

The capability to do frequency response function calculations was added to the DSNP computer code. This code was upgraded to allow generation of MFBS, PRBS, QRBS, or PRTS pseudo-random discrete-level sequences, incorporate the selected sequence into a dynamic calculation and determine the system frequency response.

Comparisons were made between the theoretical frequency response, derived with the DSNP version of the EBR-II primary system model, and experimental results. These comparisons indicate that the model heat transfer coefficients are conservative.

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REFERENCES

1. H. A. LARSON, and I.A. ENGEN, "On-Line Reactivity Feedback Analysis of EBR-II by Rod Drop," *Nuclear Technology*, 15, 462 (1972).

2. H.A. LARSON, and I. A. ENGEN, "EBR-II Feedback Transfer Function Comparison for Rod-Drop and Rod Oscillator Experiments," *Nuclear Technology*, 18,194 (1973).

3. T. W. KERLIN, *Frequency Response Testing in Nuclear Reactors*, Academic Press, New York (1974).

4. D. SAPHIER, "The Simulation Language of DSNP: Dynamic Simulator for Nuclear Power Plants," ANL-CT-77-20, Rev. 02 Argonne National Laboratory (1978).

5. H. A. LARSON et al., "Installation of Automatic Control at Experimental Breeder Reactor II," *Nuclear Technology*, 70, 167 (1985).

6. M. R. BUCKNER and T. W. KERLIN, "Optimum Binary Signals for Reactor Frequency Response Measurements," *Nuclear Science and Engineering*, 49, 255 (1972).

7. R. E. UHRIG, *Random Noise Techniques in Nuclear Reactor Systems*, Ronald Press, New York, (1975).

8. M. R. BUCKNER, "Optimum Binary Signals for Frequency Response Testing," ORNL-TM-3198, Oak Ridge National Laboratory (1970).

9. T. W. KERLIN, "Experiences with Dynamic Testing Methods at the Molten-Salt Reactor Experiments," *Nuclear Technology*, 10, 103 (1971).

10. R. A. HARRIS et al., "Multifrequency Binary Sequence Testing at the Fast Flux Test Facility," *Nuclear Science and Engineering*, 103, 294 (1989).

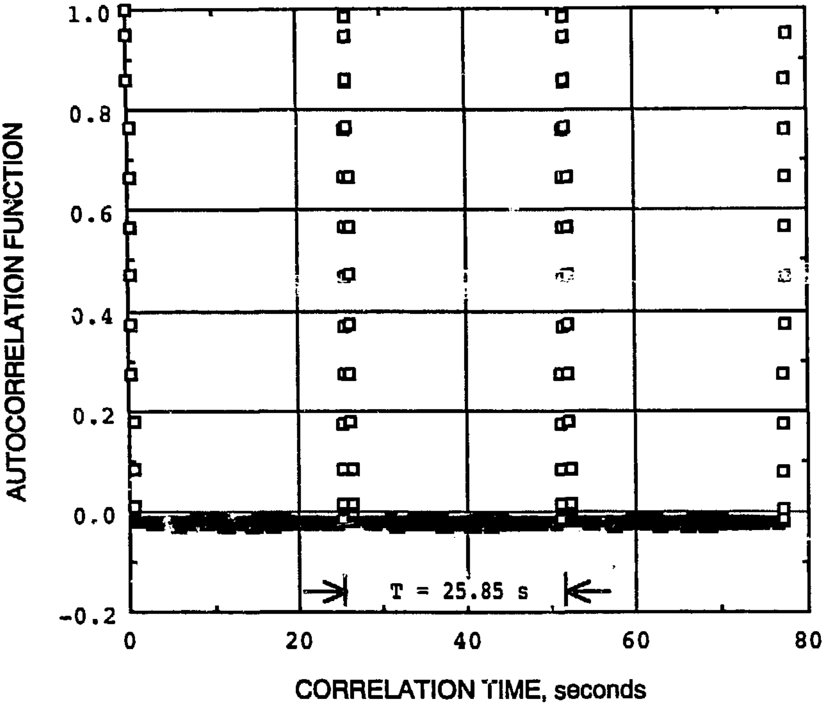


Fig. 1. Autocorrelation function of the 47 bit ± 0.011 $ QRBS test.

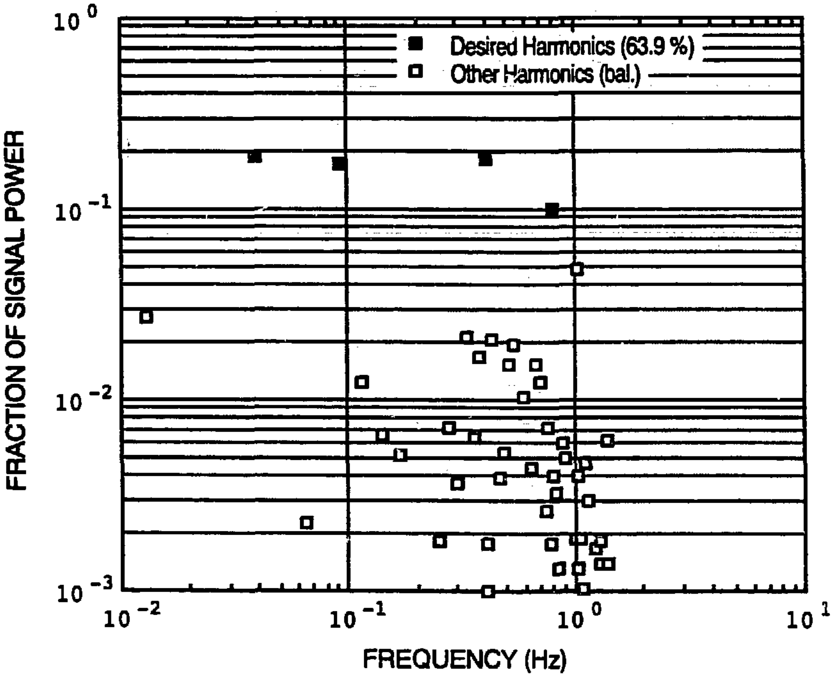


Fig. 2. Power spectrum of 140 bit MFBS test with ± 0.011 $ amplitude.

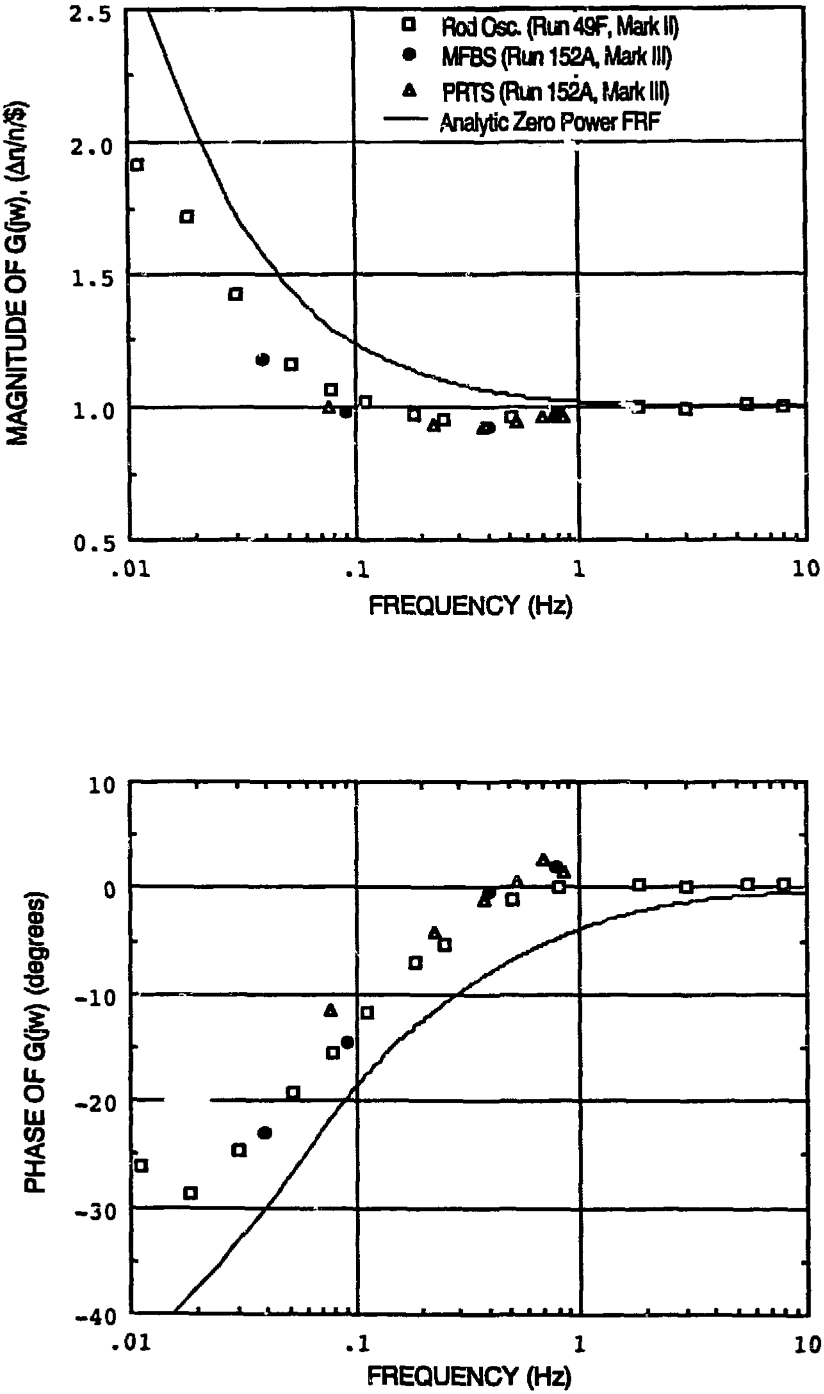


Fig. 3. EBR-II system frequency response measured with rod osc. and DLB antisymmetric ±0.011 $ signals.

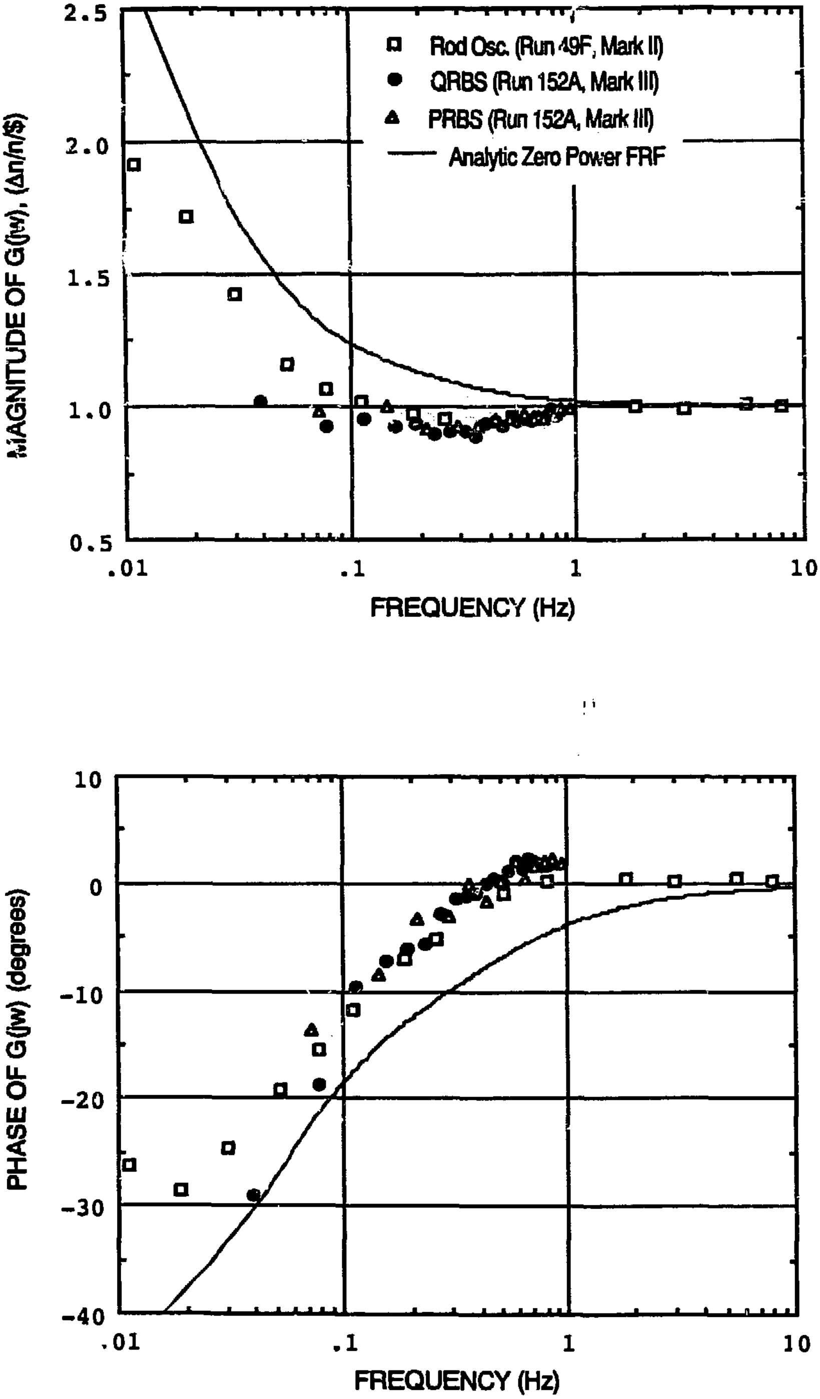
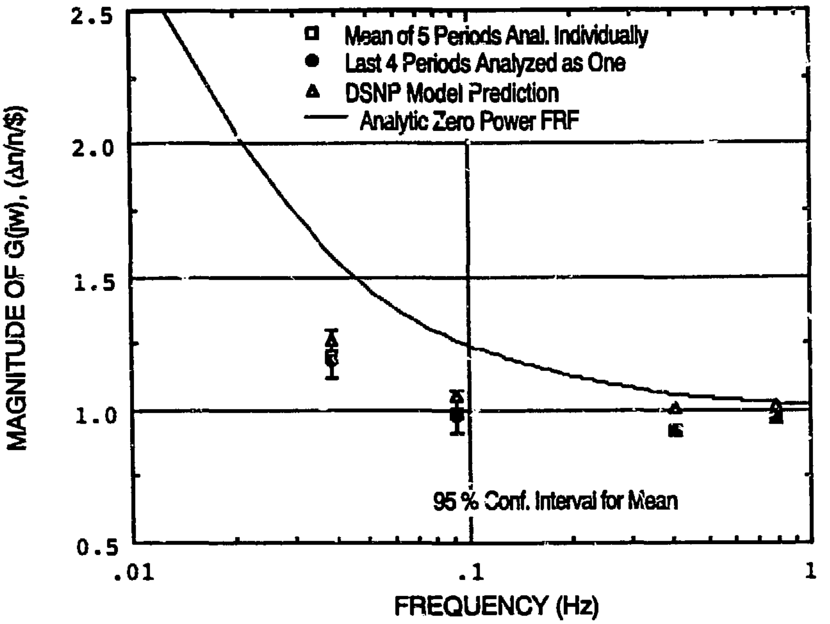


Fig. 4. EBR-II system frequency response measured with rod osc. and DLB ± 0.011 $ signals.



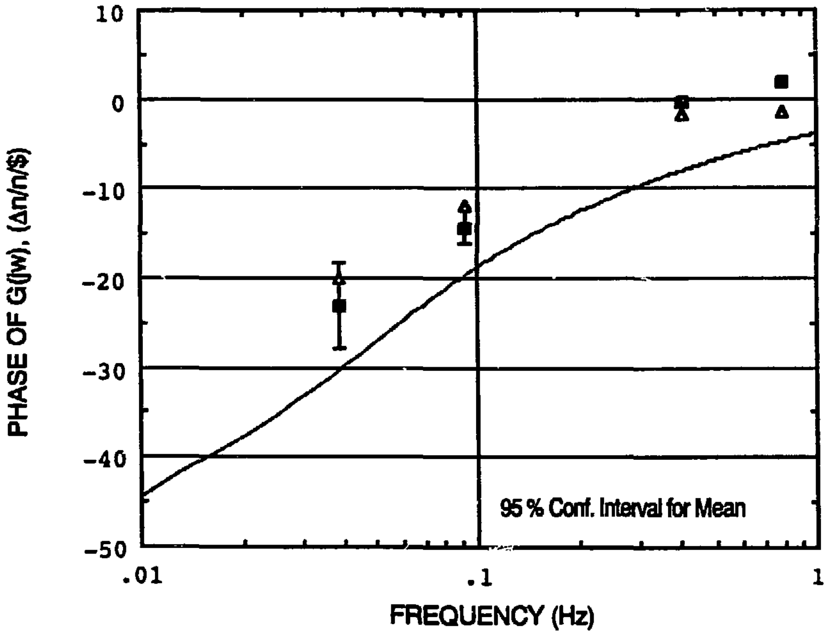


Fig. 5. EBR-II System frequency response measured with a 140 bit, ± 0.011 $ amplitude, six period MFBS test.

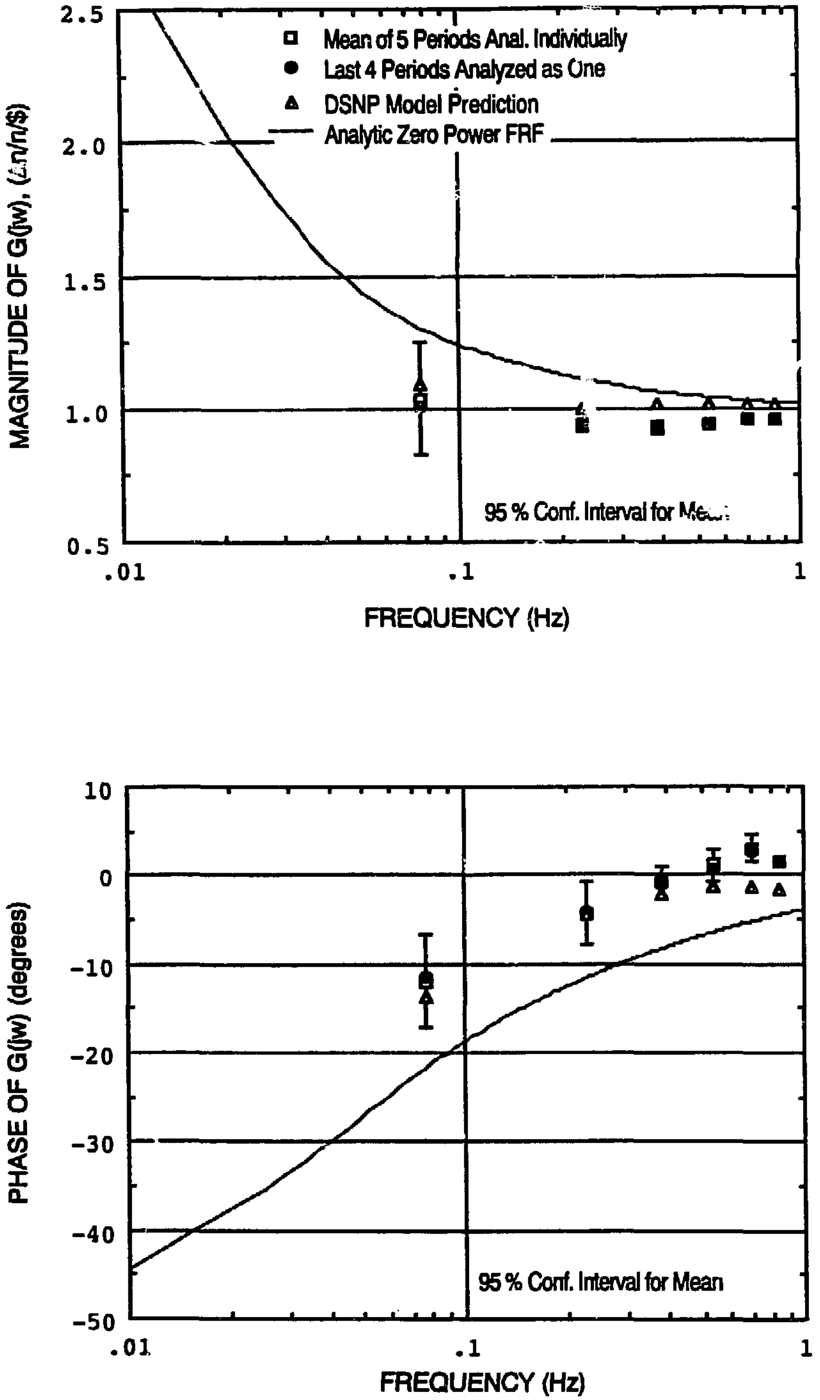


Fig. 6. EBR-II System frequency response measured with a 26 bit, ± 0.011 $ amplitude, six period PRTS test.

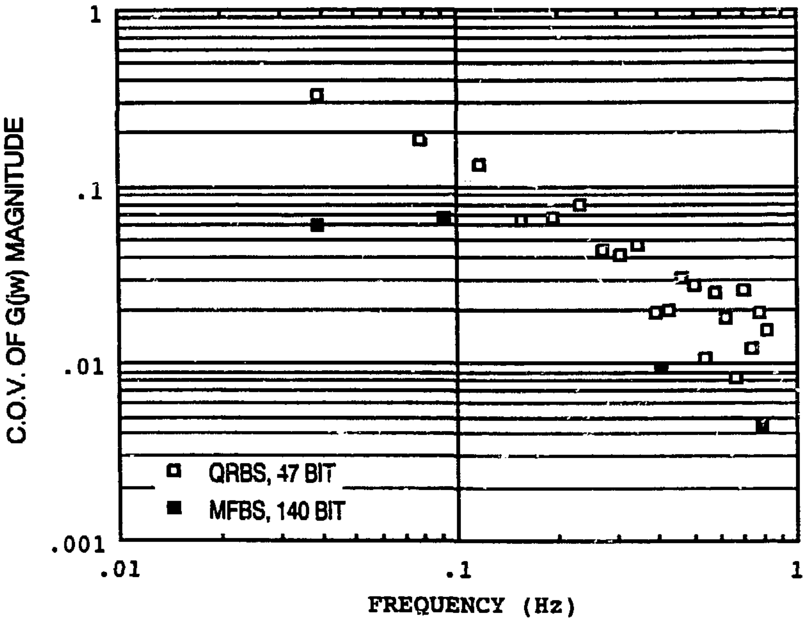


Fig. 7. Coefficient of Variation of measured frequency response magnitude, based on five periods of data, from ± 0.011 $ QRBS and MFBS tests.